



BNL-77529-2007-CP

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Presented at the 22nd Particle Accelerator Conference (PAC)
Albuquerque, New Mexico
June 25 – 29, 2007

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Overcoming Depolarizing Resonances in the AGS with Two Helical Partial Siberian Snakes *

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Abstract

Dual partial snake scheme has provided polarized proton beams with 1.5×10^{11} intensity and 65% polarization for the Relativistic Heavy Ion Collider (RHIC) spin program. To overcome the residual polarization loss due to horizontal resonances in the Brookhaven Alternating Gradient Synchrotron (AGS), a new string of quadrupoles have been added. The horizontal tune can then be set in the spin tune gap generated by the two partial snakes, such that horizontal resonances can also be avoided. This paper presents the accelerator setup and preliminary results.

INTRODUCTION

Acceleration of polarized beams to high energy in circular accelerators is difficult due to numerous depolarizing resonances. During acceleration, a depolarizing resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. In the presence of the vertical dipole guide field in an accelerator, the spin precesses $G\gamma$ times per orbit revolution, where $G = (g - 2)/2 = 1.7928$ is the gyromagnetic anomaly of the proton, and γ is the Lorentz factor. The number of precessions per revolution is called the spin tune ν_s and is equal to $G\gamma$ in this case.

There are two main types of depolarizing resonances: imperfection resonances, which are driven by magnet misalignments; intrinsic resonances, driven by the vertical betatron motion through quadrupoles. The resonance condition for an imperfection resonance is $\nu_s = n$, where n is an integer. The resonance condition for an intrinsic resonance is $\nu_s = nP \pm \nu_y$, where n is an integer, $P = 12$ is the super-periodicity of the AGS, and ν_y is the vertical betatron tune.

PARTIAL SIBERIAN SNAKES

An arrangement of magnets as a local spin rotator, called a Siberian snake [1], can overcome both imperfection and intrinsic depolarizing resonances. For a ring with a partial snake (a local spin rotator) with strength s , the spin tune ν_s is given by

$$\cos \pi \nu_s = \cos s\pi/2 \cos G\gamma\pi, \quad (1)$$

where $s = 1$ corresponds to a full snake, which rotates the spin by 180° . When s is small, the spin tune is nearly equal to $G\gamma$ except when $G\gamma$ equals an integer n , where the spin tune ν_s is shifted away from the integer by $\pm s/2$. Thus, the partial snake creates a gap in the spin tune at all integers. Since the spin tune never equals an integer, the imperfection resonance condition is never satisfied. Thus the partial snake can overcome all imperfection resonances, provided that the resonance strengths are much smaller than the spin tune gap created by the partial snake [2].

A partial snake is particularly interesting to intermediate energy synchrotrons such as the AGS, since a full snake would not fit in the available straight sections. Since the depolarizing resonance strength is not very strong, a strong enough partial snake can generate a large enough spin tune gap to overcome both intrinsic and imperfection resonances, as long as the vertical tune is placed inside the gap. The challenge is to run the synchrotron with a tune close to an integer.

For a strong partial snake, however, polarization loss at injection and extraction is no longer negligible. A 20% (36° spin rotation) snake would lead to a 10% polarization loss due to this spin direction mismatch. A single additional partial snake located in the AGS can provide the spin direction matching at injection and extraction and also increase the effective partial snake strength if its position is chosen properly [3]. Separating the two partial snakes by one third of the ring is of particular interest since it will introduce a periodicity of three units in the spin tune dependence on $G\gamma$. Since both the super-periodicity of the AGS (12) and the vertical betatron tune (9) are divisible by three, the spin tune will be the same at all intrinsic resonances, namely for $G\gamma = 3n$. With both snakes at equal strength, the effective snake strength doubles at $G\gamma = 3n$. At the injection and extraction energies, for which $G\gamma = 3n + 1.5$, the two snakes cancel. The polarization direction in the AGS is therefore exactly vertical, and no polarization is lost due to spin direction mismatch. Even using the presently installed warm helical partial snake with a rotation angle of 10.6° (or 5.9%) at extraction energy, a very substantial reduction of the injection and extraction spin mismatch can be achieved. At the same time the effective strength of the partial snakes at the strong intrinsic resonances is significantly increased.

The 5.9% normal conducting (warm) partial snake has been installed in 2004 [4]. The super-conducting (cold) partial snake has been used for RHIC polarized proton operation for the first time in 2006 [5]. The cold snake is capable of being a 20% partial snake. Since spin matching

* The work was funded by NSF PHY-0552389 and DOE DE-FG02-92ER40747 and DE-AC02-98CH1-886, and with support of RIKEN(Japan).

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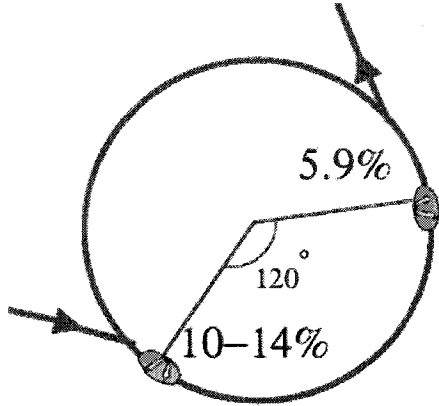


Figure 1: Locations of the partial snakes and the injection and extraction regions that give minimum polarization loss due to spin direction mismatch.

at extraction and injection is much better with two properly arranged partial snakes, we run the two snakes together. The injection and extraction regions have to be located as shown in Fig. 1 relative to the location of partial Siberian snakes. In this case the polarization loss due to injection and extraction mismatch is only 3%.

The AGS injection and extraction energies are set to occur at $G\gamma = 4.5$ and 45.5 , respectively. The extraction energy is chosen such that the spin transmission between AGS and RHIC is optimized [6]. At low energies, the helical magnets cause significant lattice distortion. Four compensation quads are added for each of the two helical snake magnets. The vertical tune is ramped into the gap at slightly higher energy after $G\gamma = 5$. With such a lattice, more than 2×10^{11} /bunch can be injected and accelerated to the RHIC injection energy. Without proper compensation quads for the warm snake, the lattice distortion reduced the dynamic aperture of AGS injection, and intensity in the AGS was limited to less than 1×10^{11} . Polarization at AGS extraction was 65% for an intensity of 1.5×10^{11} per bunch with a 10% cold partial snake and a 5.9% warm partial snake.

PARTIAL SNAKE RESONANCES

To maintain polarization in the AGS, we have to put the vertical tunes along the energy ramp into the spin tune gap generated by the two partial snakes. Moreover, due to the so-called partial snake resonances, the available tune space is even smaller. The partial snake resonances happen when

$$\nu_{sp} = k \pm l\nu_y, \quad (2)$$

where l and k are integers. When $l = 1$, these are the intrinsic resonances discussed earlier. In the presence of the snakes, the higher order resonances constrain the betatron tune space available. The strength of these snake resonances is proportional to the intrinsic resonance strength nearby. In general, the higher the resonance order, the weaker the resonance strength. The polarization mea-

surements shown in Fig. 2 depict the effect of the snake resonances for two resonances with different resonance strength. As can be seen, there is no polarization dip when $\nu_y > 8.92$ for $12 + \nu_y$, because this resonance strength is relatively weak. In contrast, there are three polarization dips for $36 + \nu_y$, where the intrinsic resonance is strong. As these data indicated, for weak intrinsic resonances, the snake resonance is not important.

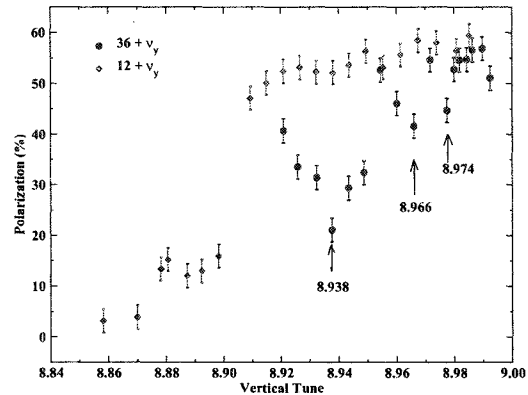


Figure 2: Polarization as function of vertical tunes at two intrinsic resonances with different resonances strength. The location of high order snake resonances near intrinsic resonances $36 + \nu$ are marked.

OVERCOMING HORIZONTAL RESONANCES

In general, intrinsic resonances are primarily associated with the vertical betatron tune ν_y for a vertical polarization, as the vertical spin can only be affected by the horizontal magnetic field. However, in the presence of a partial snake, the stable spin direction is not purely vertical. For the horizontal component of polarization, the vertical magnetic field can drive spin resonances. Therefore, the perturbing fields that rotate the spin away from the stable spin direction have vertical as well as horizontal components. Particles undergoing horizontal betatron oscillations encounter vertical field deviations at the horizontal oscillation frequency. As a result, resonances are driven by the horizontal betatron oscillations, and will occur whenever the spin tune satisfies $G\gamma = k \pm \nu_x$, where k is an integer [7]. To avoid these horizontal spin resonances, the horizontal betatron tune should also be put into the spin tune gap generated by the partial snakes. However, such optics are difficult to achieve. The effect of horizontal spin resonances is proportional to the partial snake strength. The total snake strength is then a compromise between overcoming vertical intrinsic resonances and minimizing the effect of horizontal resonances. For this reason, a combination of 10% cold partial snake and 5.9% warm partial snake was used in run 2006.

One way to eliminate the depolarizing horizontal resonances is to put the horizontal tune into the spin tune

gap. Since these resonances are generally weak, they do not need to be as high as the vertical tune to avoid snake resonances. However, due to the tune spread, they should still have some distance from the lower edge of the spin tune gap. With two unequal partial snakes, the spin tune gap varies. As the vertical tune is around 8.98, it is hard to push the horizontal tune above 8.96. Then the cold snake strength needs to be strong to provide large enough spin tune gap. For a 10% cold snake and 5.9% warm snake, the spin tune gap will vary between 0.92 and 0.96, which makes the spin tune gap too small. A 14% cold snake combined with a 5.9% warm partial snake will have spin tune gap that varies between 0.90 to 0.94. This is enough to put two betatron tunes within the spin tune gap.

Due to the significant lattice distortion at lower energy, where the effect from snakes are large, the horizontal tune can not be pushed high there. Instead, the horizontal tune started low and was pushed to about 8.95 after $G\gamma = 27$. To increase the strength of quadrupoles, twelve existing quadrupoles have been added to the vertical string. With these extra quadrupoles, both tunes can be pushed higher, but the horizontal quads are not powerful enough to bring the horizontal tune into the spin tune gap at higher energies. With large natural horizontal chromaticity, the beam radius was moved inward to generate the needed tune shift. With the radius shifted by about 10 mm, the horizontal tune was raised by about 0.1 unit. As the result, the horizontal tune was pushed into the spin tune gap above $G\gamma = 27$, as shown in Fig. 3.

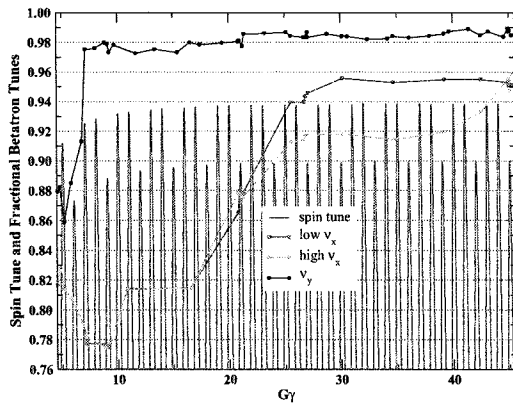


Figure 3: Fractional part of measured betatron tunes along the energy ramp and spin tune. Note that the vertical tune has to be high to avoid partial snake resonances.

A test was carried out by comparing the two lattices with high and low horizontal tunes in the later part of the energy ramp. For comparison, the horizontal tune was lowered by delaying the start of the radial shift. The two lattices were carefully set up so that the only difference between them was the horizontal tune: there was no difference in vertical tune along the ramp, 9th orbit harmonics, and AGS flat-top setup. Horizontal polarization profiles were measured for both cases. The results are shown in Fig. 4. The po-

larization values were higher with high tune case and the polarization profile was also flatter for the high tune case. Both suggests that the polarization is better with the horizontal tune in the spin tune gap. More studies are underway to fully understand the effect.

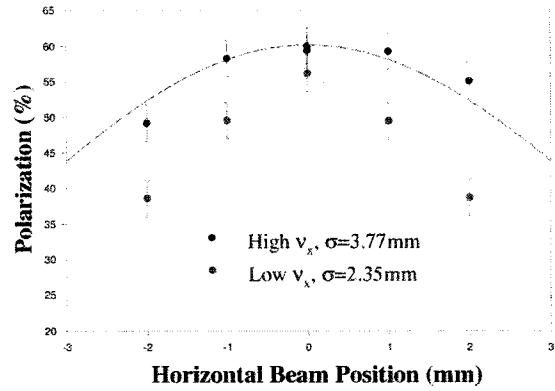


Figure 4: Horizontal polarization profiles for the two horizontal tune settings.

CONCLUSION

Acceleration of 1.5×10^{11} protons to 23 GeV with 65% polarization was achieved in the AGS using 5.9% and 10% helical partial snakes. The two-snake scheme avoids depolarization from both imperfection and intrinsic spin resonances in medium energy accelerators and also maintains good matching to the vertical polarization in the injection and extraction beam lines. The spin tune gap can be increased with a 14% cold snake. Pushing the horizontal tune into the increased spin tune gap improves the polarization. The effort continues to improve polarization by working on other possible polarization losses [8].

ACKNOWLEDGMENT

The authors would like to thank all coordinators and operators in the main control room for their help in the machine tuning, all engineers and technicians who have contributed to the polarized proton development.

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